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FORCED-AIR PRECOOLING OF CITRUS FRUIT ON A MOVING CONVEYOR

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FORCED-AIR PRECOOLING OF CITRUS FRUIT ON A MOVING CONVEYOR

By
W. Grierson, A. H. Bennett, and E. K. Bowman[1]

SUMMARY

In order to find a practical method for rapid forced-air precooling of citrus fruits, tests were conducted with an experimental prototype commercial forced-air precooler to determine the cooling rate and quantity of heat removed in relation to fruit size and length of cooling period for citrus fruit in various types of containers and in bulk. The container studies included tests with Valencia oranges, Pineapple oranges, Temples,[2] and Duncan grapefruit cooled in open and closed wirebound boxes, open and closed cartons, perforated polyethylene bags, polyethylene net bags, and shrink-film trays. Some special tests were also conducted with insulated gift fruit containers.

Tests demonstrated that fruit in open cartons or wirebound boxes can be effectively cooled with forced air in 30 minutes by maintaining sufficient temperature differential between the fruit surface and the airstream. During this period, the mean mass-average temperature reduction for all types and sizes was 33° F. for fruit in open cartons and 38° for fruit in open wirebound boxes. Closing the containers cut the cooling rate in half for the 30-minute period. The 30 minutes were adequate for cooling fruit in polyethylene net Vexar bags and in shrink-film tray packs, provided the tray packs were standing on edge. In these tests the mass-average temperature was reduced by 40°. A comparable reduction for fruit in polyethylene film bags, or for fruit in shrink-film tray packs lying flat, required 45 minutes.

Size 126 and 216 Pineapple oranges were cooled in open 4/5-bushel wirebound boxes. The mass-average temperature of the larger fruit was reduced from 75° to 52° F. in 30 minutes. The smaller fruit cooled to 44° in the same time, indicating the fruit size affects the cooling rate. This effect of fruit size on cooling rate is also demonstrated with tests of fruit in bulk. In these tests, specimen Valencia oranges carried loose on the conveyor were selected at random for size and temperature measurement at entrance and exit from the precooler. Cooling rate was inversely related to both fruit size and duration of cooling period. Temperature drop was greater for size 324 in 20 minutes than for size 96 in 33 minutes. The difference between cooling rate by size was found to be statistically significant at the 5-percent level of probability for both the 20- and the 33-minute periods.

Because of operating conditions encountered during these tests, much of the refrigerating effect was lost by infiltration of hot and humid ambient air and by unusually high solar radiation. This resulted in poor performance in terms of heat removed from the fruit with respect to design refrigerating capability.

Because of the high infiltration rate, coil frosting became severe after several hours of continuous operation. However, the coil frosting observed can be satisfactorily controlled in a commercially designed system. Lack of uniform cooling across the conveyor resulted from indeterminate air distribution patterns. Turning vanes and splitters, built into the air ducts, are essential in a design of this type. Although the experimental precooler performed inefficiently, test results indicate that this concept of forced-air precooling has commercial potential for packinghouse "in-line" precooling of citrus fruit.

Special tests demonstrated that gift fruit packed in insulated containers can be subjected to subfreezing for several hours without danger of freezing.

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[2] The Temple is a chance hybrid, probably a tangor (tangerine X orange).

BACKGROUND

A practical method for rapid forced-air precooling of citrus fruit would avoid some of the problems normally associated with hydrocooling. To be effective, however, such a system must be capable of producing the desired cooling in a short time to allow the fruit to be cooled while it is moving through the packinghouse. This means that cooling must take place while the fruit is being conveyed through a system either in bulk or in some type of container. The system must also be capable of doing the job at a cost that is reasonably competitive with hydrocooling. The research reported here is concerned with solving these problems by using a simulated commercial forced-air precooling system.

Work from 1957 to 1960 at the Citrus Experiment Station, Lake Alfred, Fla., established that the keeping quality of air-cooled fruit was superior to that of hydrocooled fruit and that air cooling could be greatly accelerated if a pressure differential could be maintained across the mass of fruit to be cooled (6, 7, 8, and 9).[3] This work resulted in the development of two commercial fresh fruit precoolers which used a vertical air movement system. In the first, air moves down through a slatted floor; in the second, more sophisticated version, air rises from underfloor channels under each row of pallet boxes.

Although either system is an improvement over the "precooling" rooms in use elsewhere in the Florida citrus industry, cooling still takes several hours and extra labor is required to move the palletized loads into and out of the precooling room. A system which permits cooling the fruit rapidly as it moves through the packinghouse would eliminate extra handling and shorten the time for holding fruit before loading out. With this aim in mind, work was initiated to investigate the commercial feasibility of forced-air precooling citrus fruit on a moving conveyor.

The tests were designed to yield information on the cooling rate and quantity of heat removed in relation to fruit size and duration of cooling period. The relation of quantity of heat removed from the fruit to operating power was also evaluated. The primary question was: Can fruit be effectively and economically air cooled in continuous travel through a citrus packinghouse for packing into shipping containers? Cooling of oranges in bulk on the moving conveyor and of several citrus varieties packed in shipping containers was investigated. Primary emphasis was given to fruit temperature response of fruit on a moving conveyor subjected to progressively lower air temperature.

Early work was carried out in a stationary, laboratory scale, experimental forced-air precooler. Rapid cooling was accomplished by forcing air through the void spaces in bulk fruit at temperatures substantially below the freezing point of the fruit. Cooling rate was enhanced by exposing more surface area of fruit to the air and by maintaining a large temperature difference between the surface of the fruit and of the air. Results of this work, reported by Soule, Yost, and Bennett (10, 11, 12) and by Bennett, Soule, and Yost (3), show that citrus fruit can be satisfactorily air cooled without delaying the normal flow of fruit through a packinghouse. The work also demonstrated that citrus fruit could stand brief exposures to air substantially below the freezing point of the fruit under suitably controlled conditions.

These findings provided the basis for the design of the experimental prototype forced-air precooler used in this research (figs. 1 and 2). This equipment is described in more detail in the report by Bennett, Soule, and Yost (2).

[3] Figures underscored in parentheses refer to Literature Cited at the end of this report.

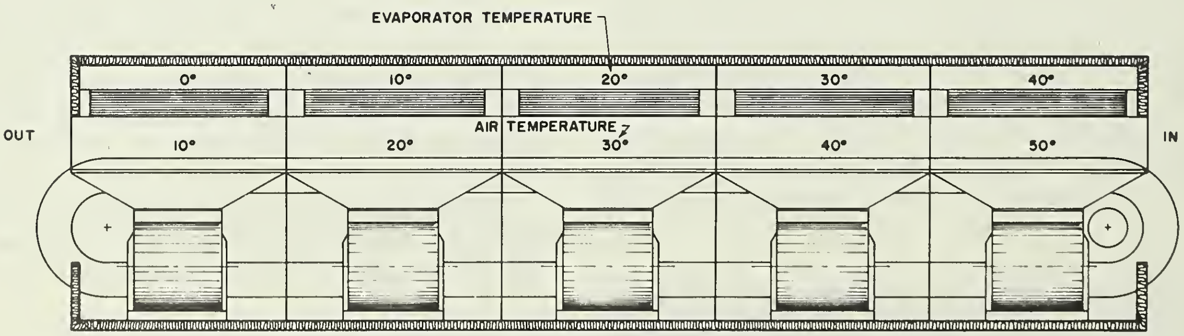

Figure 1.—Schematic side view of prototype experimental forced-air precooler. Load conditions during operation prohibited attainment of air temperature as shown.

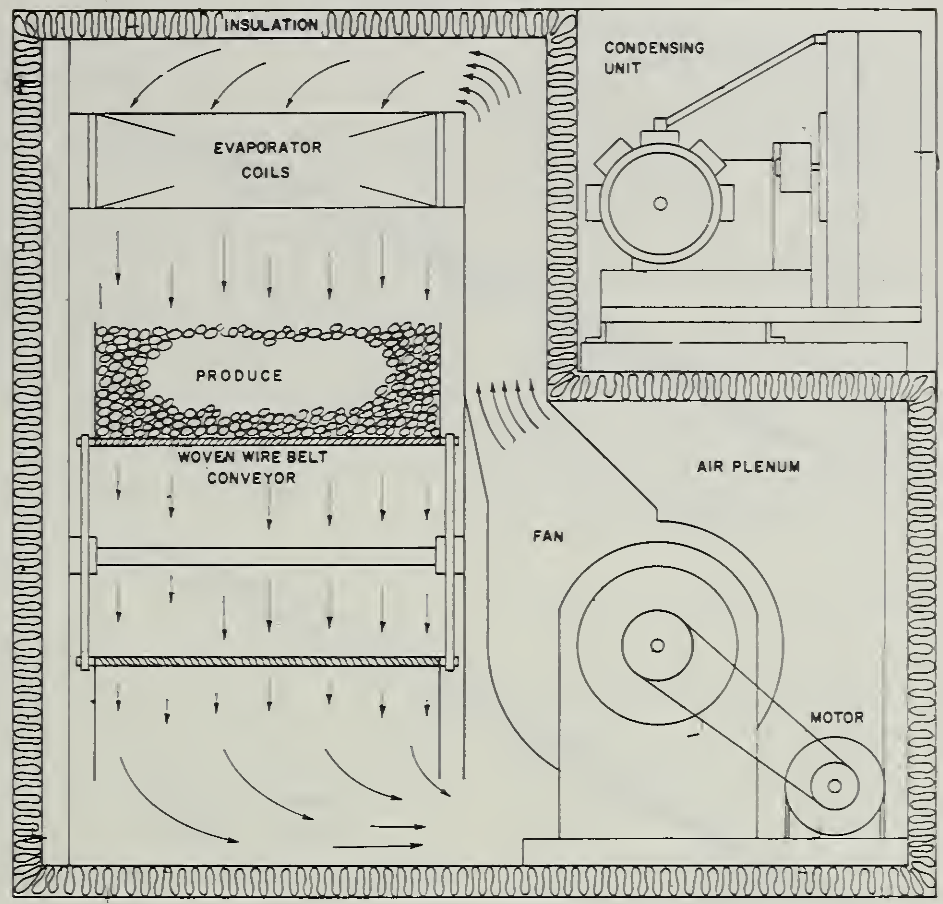

Figure 2.—Schematic end view of prototype experimental forced-air precooler.

METHODS AND EQUIPMENT

Research for this report was carried out during two seasons. Abnormal operating circumstances and unusually heavy extraneous heat load from both solar radiation and wind infiltration prohibited the precooler from performing as effectively as it should. Also, following preliminary operation in the first season (1964-65), adjustment of suction pressure regulators to provide a progressively lower air temperature in the cooling tunnel from the entrance to discharge end seriously restricted refrigerating capacity. Consequently, cooling capability was reduced. Operating under these circumstances, which prevailed until the latter part of the second season (1965-66), is denoted as condition I. Suction pressure regulator adjustment to increase refrigerating capacity and improvements to reduce wind infiltration were effected during the latter part of the second season. However, performance of the precooler was still hampered by other operating difficulties. This condition is denoted as condition II. Comparative energy requirements for the two conditions, running both loaded and empty, are illustrated in figure 3. The energy requirement for condition I was less than for condition II because of the restricted refrigeration capacity resulting from the adjustment of the suction pressure regulators during the condition I period. In addition to the normal load decrease as the system cools down, the diminishing rate of energy use is also attributable to coil icing that became severe after about 90 minutes of operation.

The precooler was located behind the experimental packinghouse and adjacent to a controlled temperature room inside the packinghouse. This room was used to achieve a uniform temperature of 85°F. in all fruit (except bulk loads) prior to testing. Ambient conditions permitted use of this procedure without causing any significant temperature change within the fruit during the time lapse between its leaving the degreening room and entering the precooler.

In the first season, limited runs with bulk fruit were conducted by warming the fruit in field boxes and dumping it manually onto the conveyor. This proved too laborious. Therefore, bulk runs were delayed until the second season. Bulk data for this first season were discarded.

Because of the lack of facilities to handle fruit in bulk on so large a scale, tests during the first season and during the early part of the second season were

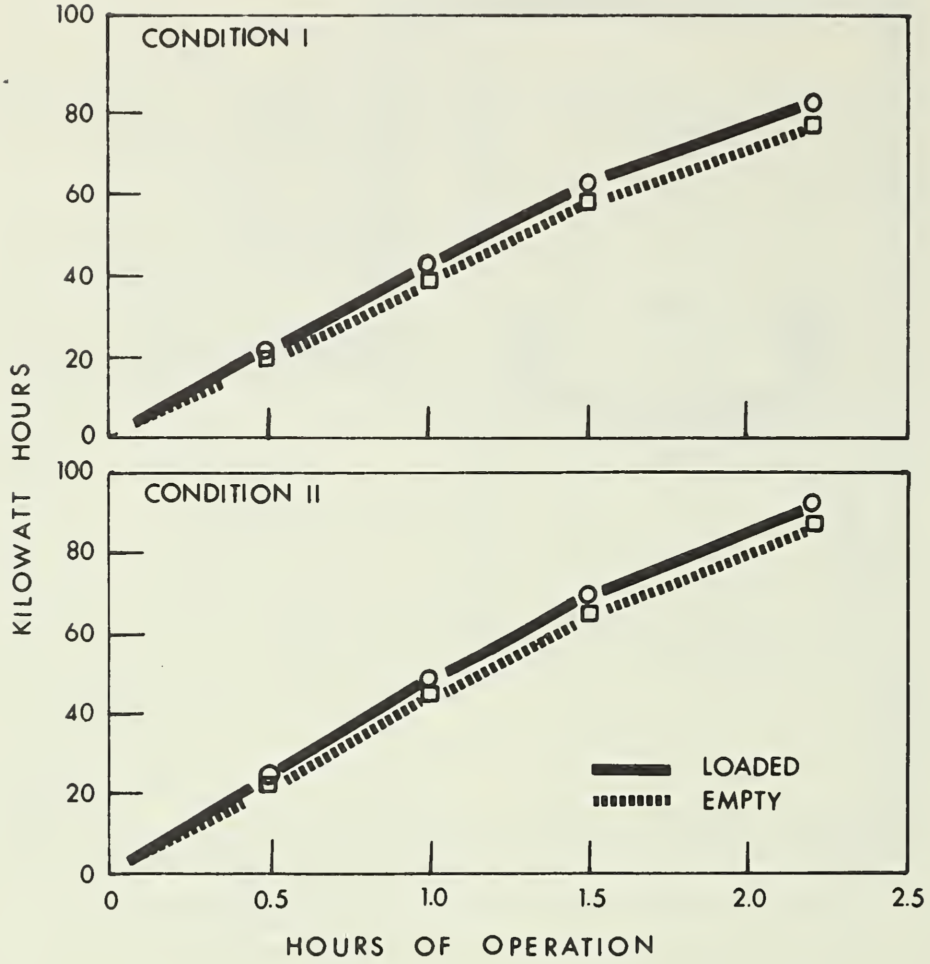

Figure 3.—Electrical energy used by forced-air precooler while operating at two conditions (machine running empty and loaded with oranges moving through the cooler in bulk).

I. Adjustment of suction pressure regulators for progressively lower air temperature in the cooling tunnel, which entailed restricted refrigerating capacity; unusually heavy extraneous heat load; abnormal operating circumstances.

II. Adjustment of suction pressure regulators changed giving less restriction on refrigerating capacity; heavy extraneous heat load; continuing operating difficulties.

conducted with several varieties and types of fruit in various types of shipping containers and various arrangements on the belt. For most of the container experiments, temperature probes similar to those described by Bennett, Soule, and Yost (3) were connected to a 12-point recorder. Temperature from center to surface of two fruit in each test was recorded. However, only the center temperature and mass-average temperature are reported. The thermal probe was inserted in a fruit located in the center of each container. All of these tests were carried out with the precooler operating at condition I.

By the latter part of the second season, a system of conveyors was constructed that made it possible to move bulk fruit from a large, open trailer, through the packinghouse, and into the precooler. The fruit was caught at the discharge end of the precooler in a Hi-lift truck, which was weighed on truck scales to accurately determine the weight of the fruit cooled. Approximately 3 tons of fruit were cooled in a single continuous run. These tests were carried out with the precooler operating at condition II.

Cooling rates for all tests are reported in terms of time rate of mass-average temperature reduction, °F. per min., or total mass-average temperature reduction, °F. This means of reporting temperature was made possible by maintaining a constant initial temperature for fruit in all tests. Mass-average temperature was measured at entrance and at discharge of the cooling tunnel.

Total energy consumption for all equipment components was measured by means of a watt-hour meter on the power intake to the precooler. Air temperature under the cooling coils, in each fan chamber, and in the air delivery duct above the cooling coils was sensed by thermocouples and recorded on a 16-point recorder.

Container Tests

Valencia oranges, Pineapple oranges, Temples, and Duncan grapefruit were cooled in open and closed wirebound boxes, open and closed cartons, perforated polyethylene bags, polyethylene net bags, and shrink-film trays. Except as noted, all container tests were carried out at operating condition I. Some special tests were also conducted with fruit in insulated fiberboard containers used for shipping gift fruit. For these, the test lot of fruit was held stationary under the coil of the lowest temperature unit for the entire test period.

Matched Pairs of Oranges and Grapefruit

A study to compare the cooling rate of oranges with grapefruit of the same size was conducted during the first season. For this study two boxes each of size 96 oranges and grapefruit were selected. Each fruit was weighed and sized until five matched pairs of one orange and one grapefruit were selected. Each pair was then placed in a small bag of polyethylene net to keep the two fruit in constant juxtaposition. A thermal probe was then inserted into each fruit. After cooling, the fruit was cut open and peel thickness was measured. Five test runs were conducted—three with fruit packed in unlidded cartons and two with fruit loose on conveyor. Cooling time was regulated by manually controlling the speed and intermittent operation of the conveyor. Results of these tests are given in table 1. The difference in cooling rate between the grapefruit and the oranges is greater than would be expected on the basis of investigations of thermal properties of the rind and juice vesicles of grapefruit and oranges, by Bennett, Chace, and Cubbedge (1). The cause of the wide difference between fruit in the carton and that in bulk is not known. It might possibly be attributable to the effect of position on the conveyor. This is discussed in more detail in a following section.

TABLE 1.—Cooling rate of matched pairs of size 96 oranges and grapefruit

Method of handling and cooling period[1] (min.)	Temperature reduction	
	Oranges[2]	Grapefruit[3]
Center of open 4/5-bu. carton:	*°F./min.*	*°F./min.*
162	0.30	0.28
108	.72	.27
54	1.00	.74
Bulk lot:		
54	.54	.52
60	.50	.43

[1] Cooling longer than 60 min. was achieved by periodically stopping the conveyor.
[2] Average, 5 pairs; weight, 375 g.; major diameter, 3.63 in.; minor diameter, 3.34 in.; peel thickness, 0.22 in.
[3] Average, 5 pairs; weight, 381 g.; major diameter, 3.69 in.; minor diameter, 3.38 in.; peel thickness, 0.25 in.

Two Sizes of Pineapple Oranges

With the conveyor set to maintain a travel time through the tunnel of 50 minutes, tests were run with 4/5-bushel wirebound boxes (top open) containing size 126 and 216 Pineapple oranges, respectively. Temperature history of each size was recorded at the center and at the mass-average point. Figure 4 illustrates the effect of size on cooling rate.

Type of Container—Size and Type of Fruit

A comparative evaluation of cooling rate for sizes 126 and 216 Temples and Pineapple oranges and sizes 70 and 126 Duncan grapefruit was conducted at each of five cooling periods and with four types of containers arranged as follows: (1) Cartons open and closed, (2) wirebound boxes open and closed, (3) mesh and polyethylene bags, and (4) shrink-film tray packs laid flat and on edge. The wirebound boxes and cartons were standard Florida citrus containers of 4/5-bushel capacity (5). The polyethylene film bags had the regulation 72 holes of 1/4-inch diameter. The Vexar bags were light polyethylene mesh that offered no resistance to air movement. Each bag was of 5-pound capacity. The shrink-film trays were selected to accommodate the type and size of fruit being tested. When filled with Pineapple oranges and Temples the trays held two rows of fruit. Turning them on end provided an air channel through the package. With grapefruit, the typical package held two or three in a single row. Hence, no such air channel was provided.

The results are presented in tables 2 and 3 in terms of reduction in mass-average temperature in ° F. per minute. Total mass-average temperature reductions by fruit and container type with respect to duration in the cooling tunnel are illustrated in figures 5 and 6. The effect by fruit type is shown in figure 5. Figure 6 shows effect by type and arrangement of container.

The substantially superior response of the Temple orange, indicated in figure 5, agrees with findings reported earlier by Soule, Yost, and Bennett (12).

As shown in table 4, cooling cannot be satisfactorily achieved in most shipping containers. Fruit in open wirebound boxes cooled acceptably well, but these containers are awkward to handle with the lid open; and for various reasons their use is decreasing rapidly, except for tangerines and certain specialty fruit. As noted, the Vexar bag is an ideal container for use in forced-air precooling. This is because air can be circulated through

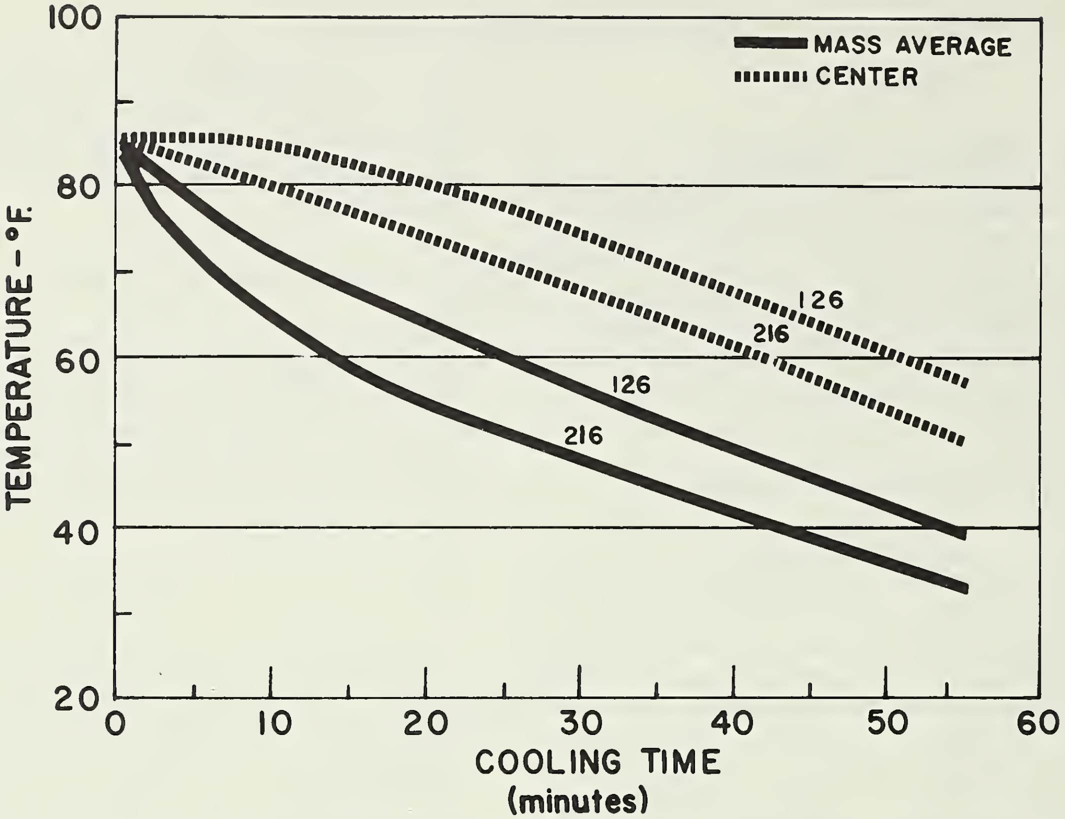

Figure 4.—Center and mass-average temperature response of size 126 and 216 Pineapple oranges during cooling in open 4/5-bushel wirebound box.

the bag and over the surface of each individual fruit. It was difficult to arrange shrink-film trays on the belt so that air was forced through the tray and over the surface of individual fruit.

Findings reported in tables 2 and 3 represent the average from a number of individual results for each corresponding group. When reported in this way, the findings constitute a discernible pattern that allows a

TABLE 2.—Reduction in mass-average temperature, by size and type of fruit, all containers tested[1]

Fruit Type	Fruit size		Reduction in temperature per following minutes of cooling				
	Count	Avg. diam.	15	30	45	60	75
		Inches	°*F./min.*	°*F./min.*	°*F/min.*	°*F./min.*	°*F./min.*
Pineapple oranges	216	2-3/4	1.06	0.93	0.76	0.62	0.58
	126	3-1/2	1.19	1.08	.82	.61	.54
Temples	216	2-3/4	1.18	1.00	.84	.71	.62
	126	3-1/2	1.50	1.25	.99	.80	.68
Duncan grapefruit	126	3-1/2	1.26	.98	.82	.75	.65
	70	4-1/8	.86	.81	.69	.56	.50

[1]The apparent discrepancies in which small fruit cooled more slowly than large fruit are believed to be due to the impedance of air movement through the restricted air space in the voids between fruit in containers place-packed with small Pineapple oranges and Temples.

TABLE 3.–Reduction in mass-average temperature for various containers. Average data from two sizes each of Pineapple oranges, Duncan grapefruit, and Temples

Container	Reduction in temperature per following minutes of cooling				
	15	30	45	60	75
	°*F./min.*	°*F./min.*	°*F./min.*	°*F./min.*	°*F./min.*
5-lb. Vexar mesh bags	1.90	1.30	1.08	0.80	0.68
Open wirebound boxes	1.60	1.25	.95	.75	.65
Open 4/5-bushel cartons	1.30	1.12	.88	.70	.58
Shrink-film trays, on edge	1.25	1.34	1.05	.62	.70
Shrink-film trays, flat	1.30	.95	.85	.75	.55
5-lb., 72-hole, polyethylene bags	.85	.92	.88	.75	.62
Closed wirebound boxes	.85	.65	.58	.58	.53
Closed 4/5-bushel cartons	.85	.60	.45	.40	.38

meaningful evaluation of test treatments. The individual results were highly erratic, containing so much deviation that it was impossible to evaluate cause and effect. Some of the deviation was caused by variation in the location of fruit in the container, failure of equipment to perform consistently over all test runs, or experimental error in temperature measurement. However, investigations into the air distribution in the conveyor tunnel gave rise to the conjecture that location of the package on the conveyor belt was the chief source of variation.

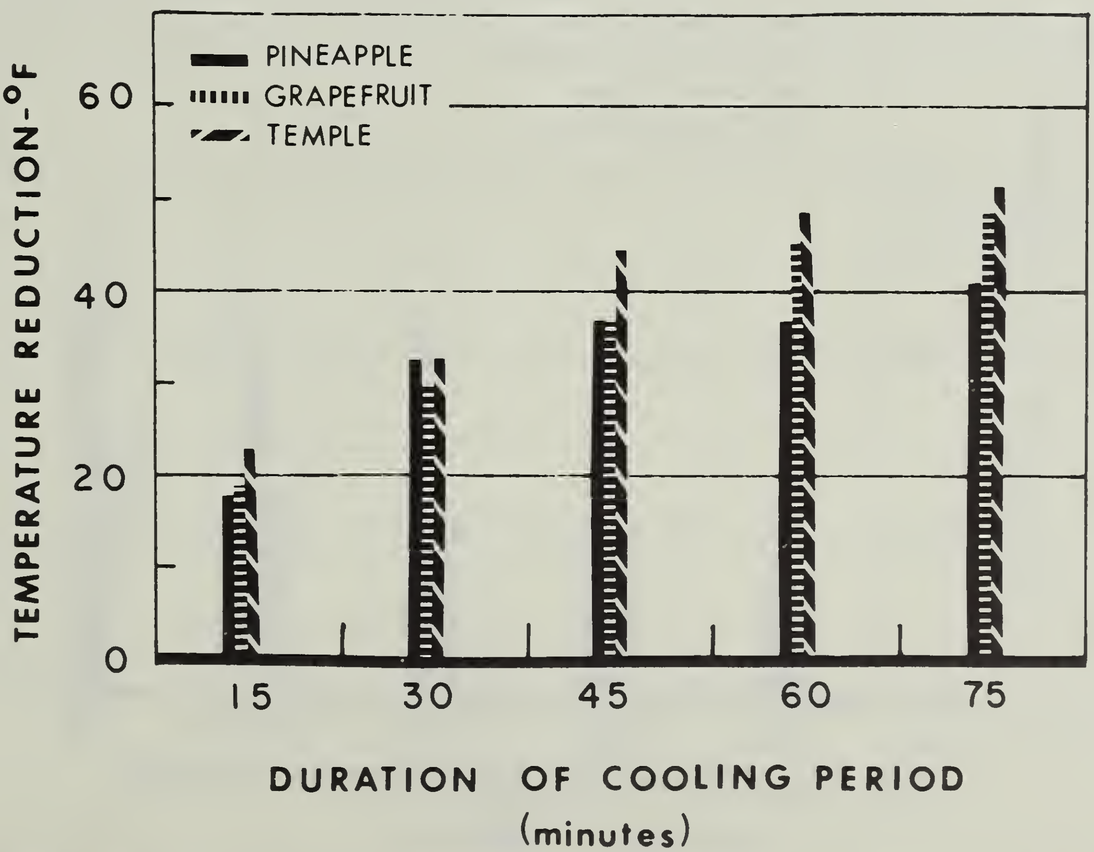

Figure 5.—Mass-average temperature reduction with respect to duration of cooling period for Pineapple oranges, Duncan grapefruit, and Temples (size 126 and 216). Values shown represent the averages of all container types and arrangements.

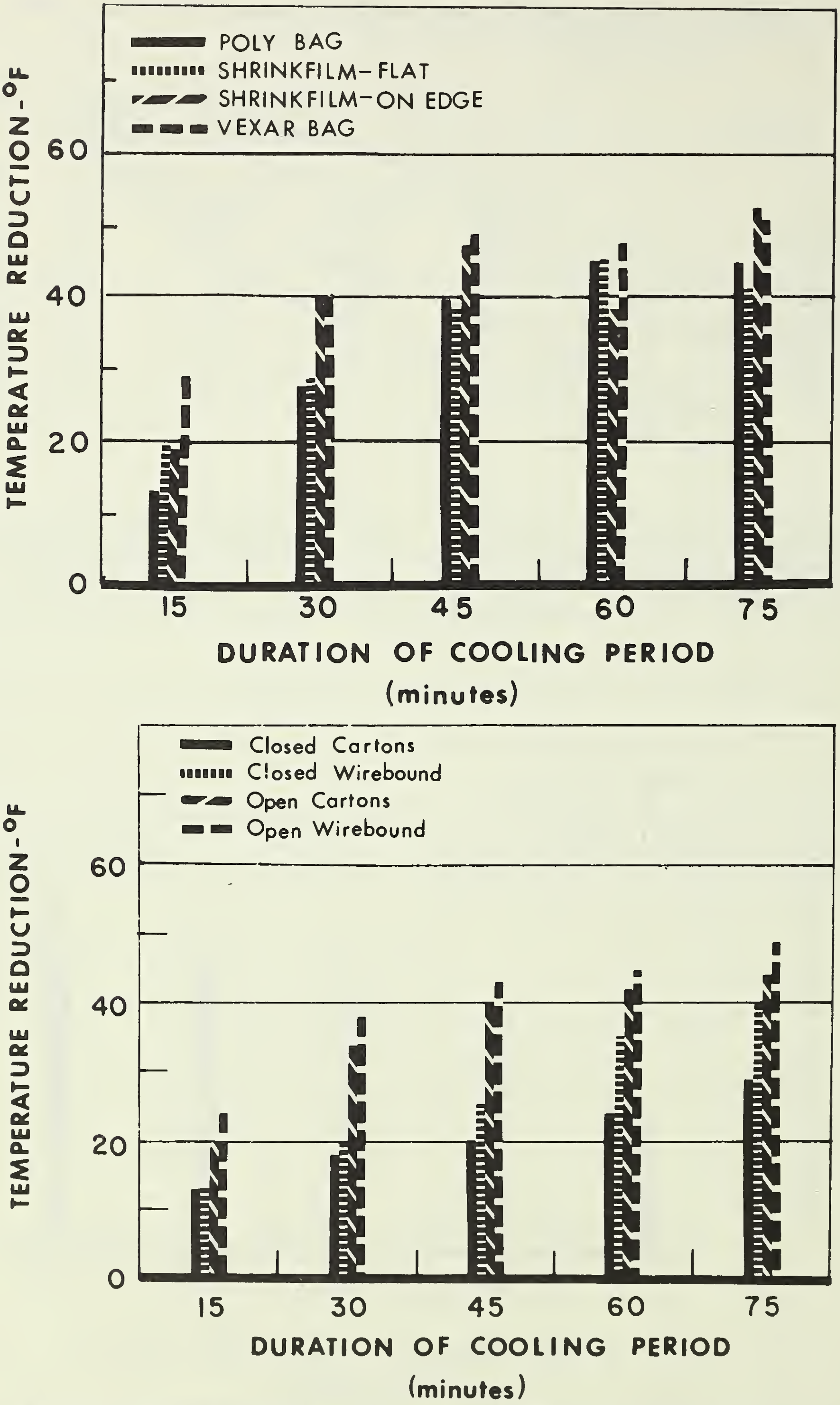

Figure 6.—Mass-average temperature reduction by container types and arrangements as shown with respect to duration of cooling period. Values shown represent averages for all fruit types.

TABLE 4.—Qualitative evaluation of container test runs listed in table 3[1]

Quality of cooling	Type of container	Evaluation
Good cooling	Vexar mesh bags; open wirebound boxes.	For short (15 min.) exposures, the Vexar bags cooled somewhat faster than the open 4/5-bushel crates. For runs over 30 min., there was little difference.
Fair cooling	Open 4/5-bushel cartons.	Fair cooling, but the distortion of the unlidded telescope carton due to dampness and lack of mechanical support was considered prohibitive.
	Shrink-film trays	Very erratic cooling due to unpredictable channeling. But 1.2° F. per minute decrease in mass-average temperature over 30 min., can be considered a fair cooling rate.
Poor cooling	5-lb. polyethylene bags; closed wirebound boxes; closed cartons.	Polyethylene bags cooled a little better than closed wirebound boxes and closed wirebound boxes a little better than closed cartons, but there was little to choose between them.

[1] For descriptions of all containers, except shrink-film trays, see Florida Citrus Commission Regulation No. 3 (5).

BULK VS. WIREBOUND CONTAINER—SMALL SCALE

Preliminary cooling rate tests with bulk Pineapple oranges and packed Valencia oranges were carried out with the equipment operating on condition I. This afforded a comparison of cooling rates for packed and bulk oranges under lightly loaded conditions (fig. 7). In these tests the bulk oranges cooled 30 percent faster in a 17-minute run and 14 percent faster in a 33-minute run than did packed oranges. With cooling runs as long as an hour, the differences in cooling rate invariably decreased, but even on 80-minute runs the bulk oranges still cooled at 0.7° F. per minute as compared with 0.65° F. per minute for fruit packed in open wirebound boxes.

LARGE SCALE BULK TESTS

During the latter half of the second season, the conveyor system having been completed, seven test runs

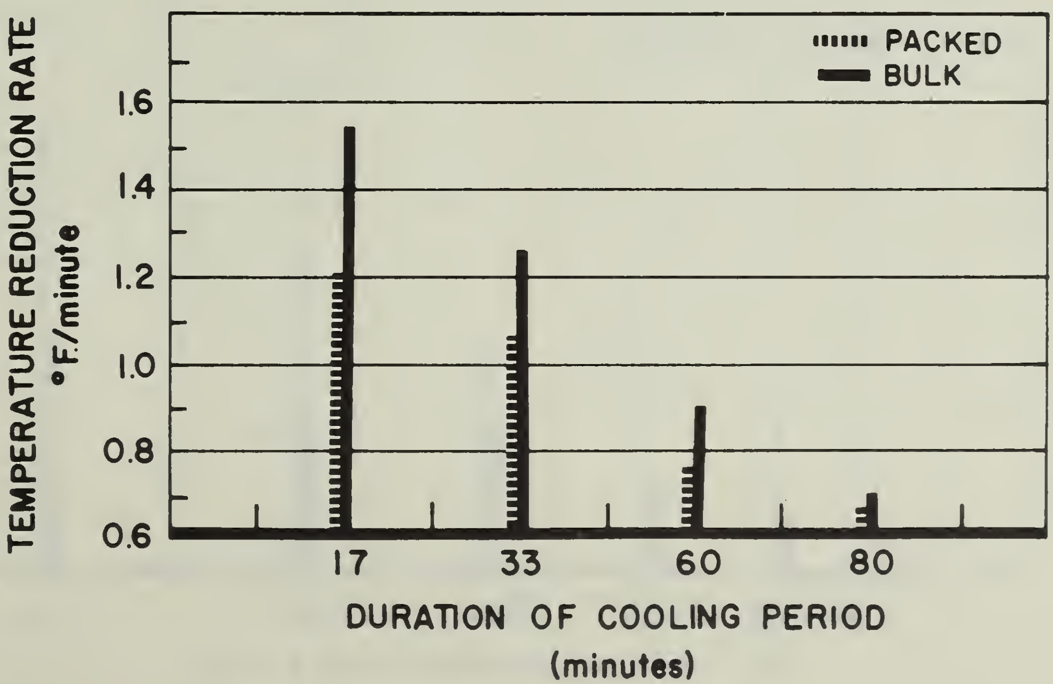

Figure 7.—Cooling rates of Pineapple oranges in bulk and Valencia oranges in open wirebound boxes with the machine under light load and operating at condition I.

were conducted with unpacked (loose) fruit placed directly on the conveyor. Each run consisted of approximately 60 equivalent boxes or 5,400 pounds of fruit. The fruit was unloaded from a semitrailer, conveyed through the packinghouse into the precooler, and conveyed out of the precooler and into a Hi-lift truck. This permitted operating the precooler continuously until the 60 boxes were cooled. Approximately 15 boxes, or 1,350 pounds, of fruit were in the cooling tunnel at one time. These runs were carried out with the precooler adjusted to operate at condition II.

Effect of Fruit Size

The mass-average temperature of selected sizes of oranges was measured at the entry and discharge ends of the precooler. Temperature was measured in fruit of each of the six standard orange sizes. Temperature was measured by inserting a thermocouple to the mass-average point of the fruit and reading the value obtained directly off the recording potentiometer. Fruit size was determined by means of a board constructed with openings having the average diameter of each of the six orange sizes. Working alternately at the entry and discharge ends of the cooling tunnel, a pair of workers picked off oranges, determined their size, inserted the thermocouple to the estimated point of mass-average temperature, and read the temperature from the indicating scale of the recording potentiometer. Entry and exit temperature observations for each fruit, grouped by size, were arrayed for analysis. Respective temperature values were paired for analysis. However, no attempt was made to measure the entrance and exit temperature of identical fruit. Entrance and exit temperature data were obtained for each fruit size during each run. The mass-average temperature reduction by fruit size for cooling periods of 20 minutes and 33 minutes is illustrated in figure 8. The 20-minute cooling time represents the average of two runs each having 110 readings of each fruit size. The 33-minute-duration test represents the average of four runs with 158 readings for each fruit size. The analysis of variance for both test periods is summarized below.

20-Minute test

Source	SS	DF	Mean Square	F Ratio
Treatment	3269.44	5	653.88	239.86**
Error	1782.87	654	2.72	
Total	5052.31	659		

33-Minute test

Source	SS	DF	Mean Square	F Ratio
Treatment	3295.22	5	1059.04	144.07**
Error	6924.54	942	7.35	
Total	12224.76	947		

** Statistically significant at the 1% level of probability.

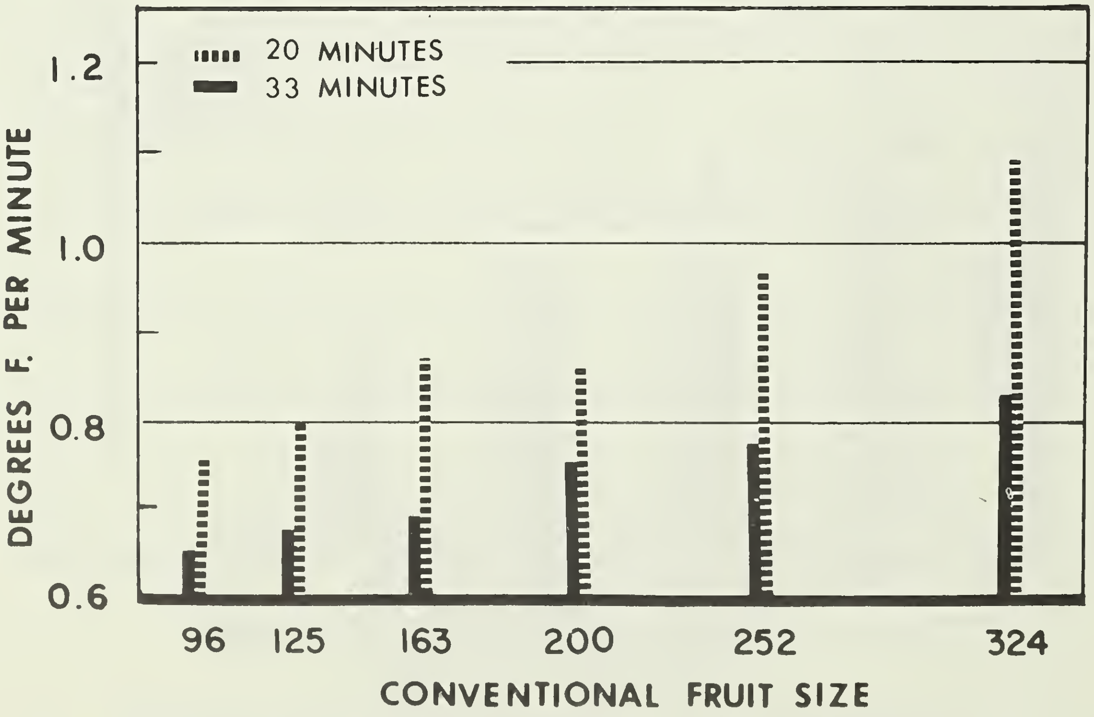

Figure 8.—Reduction of mass-average temperature by fruit size for Valencia oranges cooled in bulk for periods of 20 and 33 minutes. Initial fruit temperature was 80° F.

TABLE 5.–Statistical evaluation of temperature reduction and size relationship for Valencia oranges cooling in bulk

Size	20-Minute test: Mean temperature reduction[1]		20-Minute test: Standard deviation	33-Minute test: Mean temperature reduction[1]		33-Minute test: Standard deviation
	°F.	°F./min.		°F.	°F./min.	
96	15.09	0.75 a	1.40	20.93	0.63 a	2.44
125	15.93	.80 b	2.17	21.87	.66 b	2.44
163	17.26	.86 c	1.55	23.05	.70 c	2.90
200	17.45	.87 c	1.81	24.59	.75 d	2.48
252	19.48	.97 d	1.39	25.76	.78 e	2.72
324	21.75	1.09 e	1.39	27.90	.85 f	3.16
	r = 0.992				r = 0.997	

[1] Different letter code indicates significant differences at the 1-percent level of probability, by Duncan's New Multiple Range Test Analysis (13, pp. 107-109).

By means of Duncan's multiple range tests (13, pp. 107-109), the relationship between fruit size and cooling rate was statistically analyzed. The results presented in table 5 show the effect of individual fruit size on the mean values of mass-average temperature reduction within each size. For the 20-minute test period, all means are significantly different at the 1-percent level of probability except for sizes 163 and 200. There was no significantly different temperature reduction between these two sizes. For the 33-minute tests, all means are significantly different at the 1-percent level of probability. Correlation coefficients are based on the relationship between size and mean values of temperature reduction as listed in table 5.

Size by Count vs. Average Fruit Diameter

Consideration of the effect of fruit size on cooling rate is complicated by the lack of a direct proportion between legal standard fruit size expressed by count and fruit size expressed by average diameter (14). The relationship is illustrated in figure 9. Figure 10 illustrates

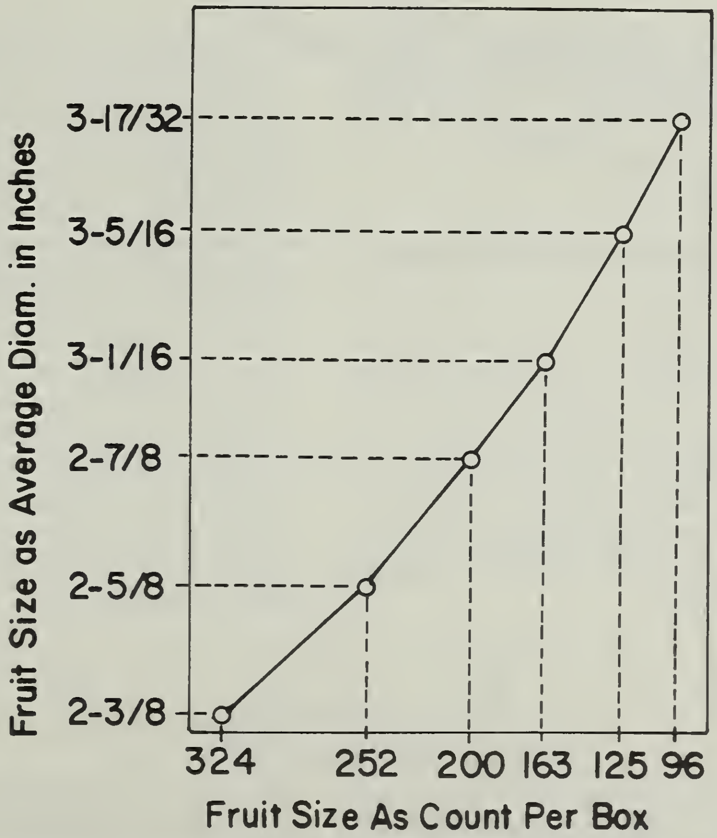

Figure 9.–Relationship of fruit size in terms of oranges per box to average fruit diameter (14).

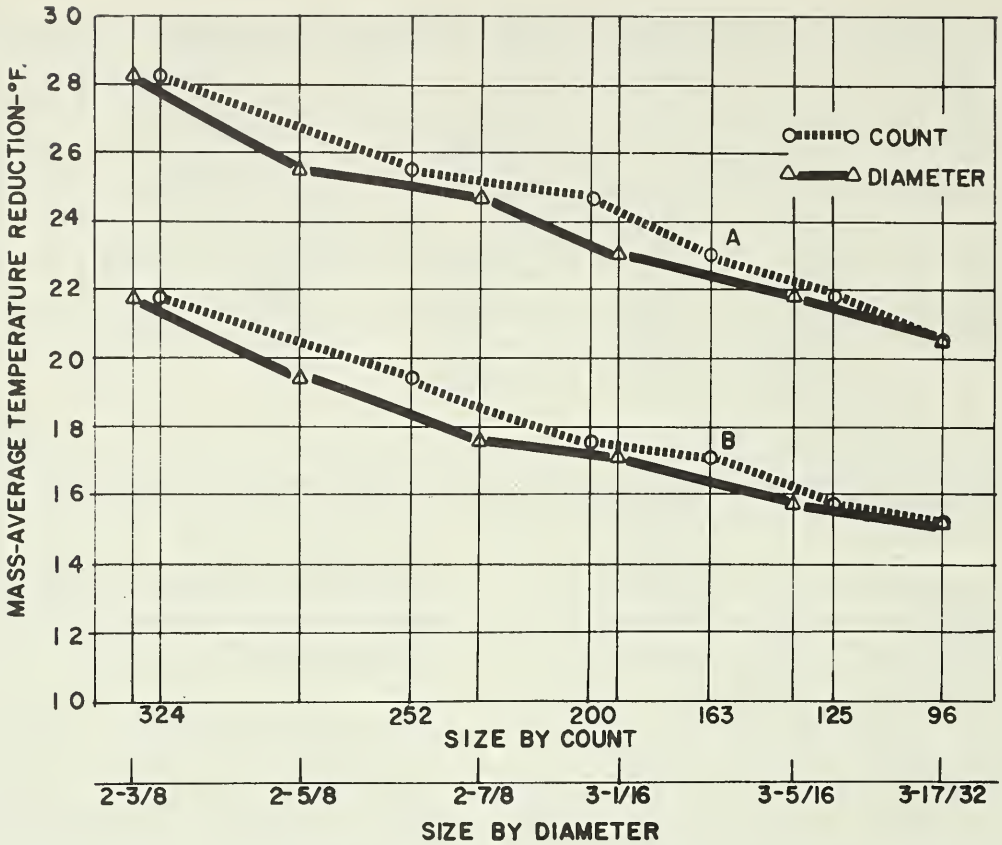

Figure 10.—Reduction in mass-average temperature of bulk-cooled Valencia oranges as related to fruit size by average diameter and by count per box.

the effect of size by count per box and by average diameter on reduction in mass-average temperature of fruit in bulk when cooled for periods of 20 and 33 minutes.

COOLING IN INSULATED GIFT FRUIT CARTONS

A considerable amount of Florida citrus is shipped by railway express in gift containers. In the interest of gift fruit shippers, tests on a new type of carton were conducted. These containers were lined with foam insulation, primarily to protect the fruit against mechanical damage, but also to reduce danger of freezing in transit. Because they pose special problems in cooling, a small scale experiment was set up using these cartons packed with Valencia oranges.

Two types of containers were tested: (1) A single thickness of corrugated fiberboard lined with 1/2-inch of polystyrene foam, and (2) a double thickness of fiberboard with 1/4-inch thick polyurethane foam pads in top and bottom of container. These were compared with cooling in a regular 4/5-bushel closed carton. Thermocouples measured mass-average temperature of one fruit located near the outer edge of each box. The fruit was cooled for 10 hours while stationary under the cooling coils that operate at the lowest temperature. Results are listed in table 6 and illustrated in figure 11. It is apparent, from these results, that nonprecooled fruit packaged in these types of containers and subjected to an airblast ranging in temperature from 2° to 20° F. for a period of 10 hours will not be in danger of freezing. Precooled fruit packed in gift cartons did not cool to a dangerous level after approximately 6 hours cooling time.

AIR DISTRIBUTION

Reasons for variation in cooling rate among treatments in the container study were investigated in a series of experiments. Size 200 Valencia oranges in net Vexar bags were distributed at various positions on the conveyor belt. Twelve net bags, each holding 5 pounds of oranges, were placed on the belt in a pattern shown in figure 12. The bags were in the cooling tunnel 15 minutes. The precooler was operating at condition II.

TABLE 6.—Prolonged cooling of insulated gift fruit containers

Container	Cooling duration	Air temp.	Fruit temperature	
			Initial	Final
Not precooled:	*Hours*	°*F.*	°*F.*	°*F.*
1-1/3-bushel polystyrene lined	10.3	8	80	38
1-1/3-bushel polystyrene + pads[1]	10.3	8	78	49
1-1/3-bushel polystyrene + pads	6.2	5	78	51
2-ply fiberboard + pads	5.2	5	79	40
Regular 4/5-bushel telescope cartons[2]	7.3	7	79	26
Regular 4/5-bushel telescope cartons[3]	7.3	7	79	20
Precooled:				
1-1/3-bushel polystyrene lined + pads	6.0	3.5	41	26
2-ply fiberboard + pads	6.0	3.5	33	29

[1] Pads were 1/4-inch polyurethane foam.
[2] Carton on fan side of belt.
[3] Carton on side of belt away from fan.

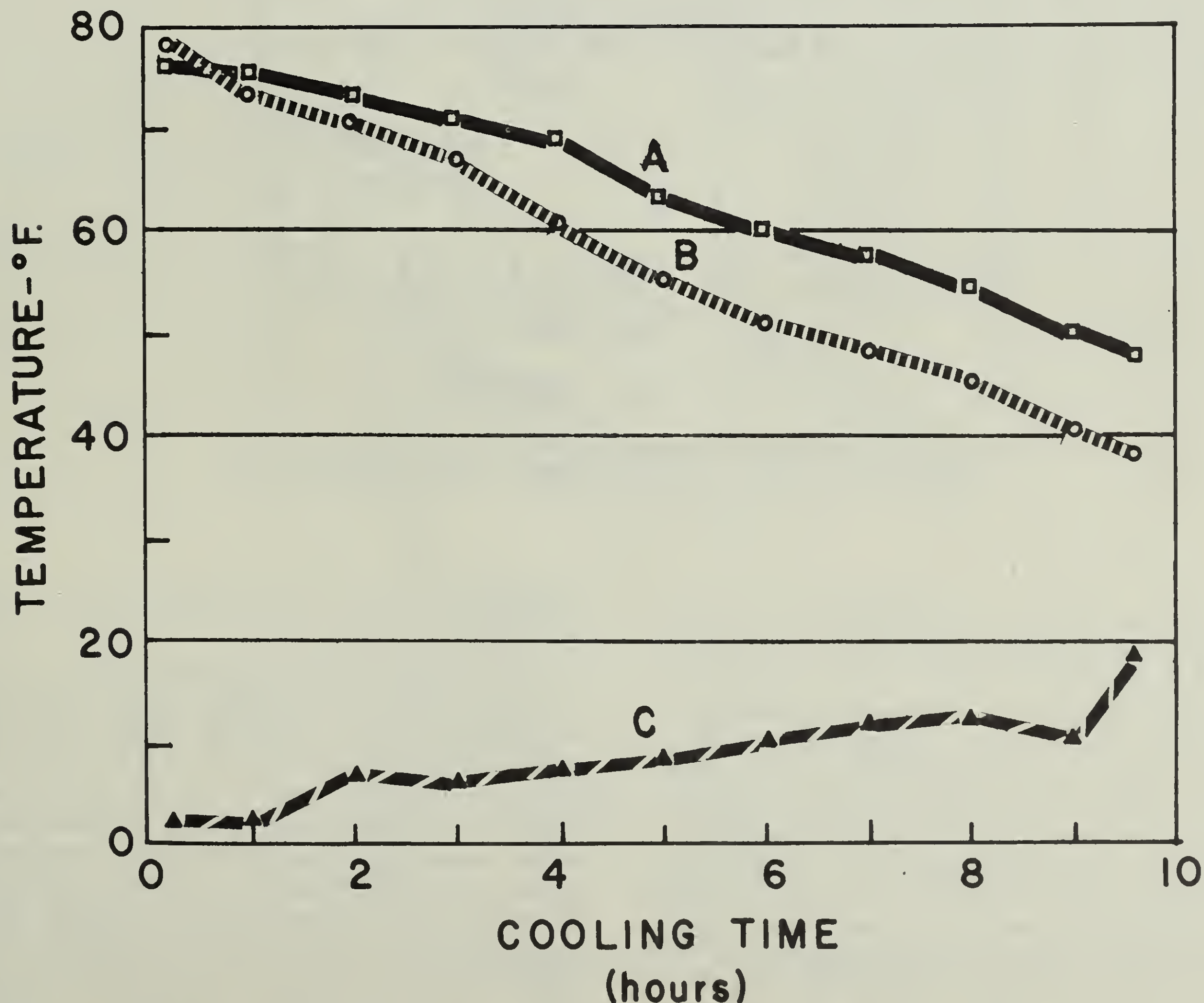

Figure 11.—Mass-average temperature response of Valencia oranges packed in: (A) Polystyrene lined gift cartons with additional polyurethane pads in top and bottom, and (B) polystyrene lined gift cartons with no pads. Curve (C) illustrates air temperature surrounding the boxes during the 10-hour period.

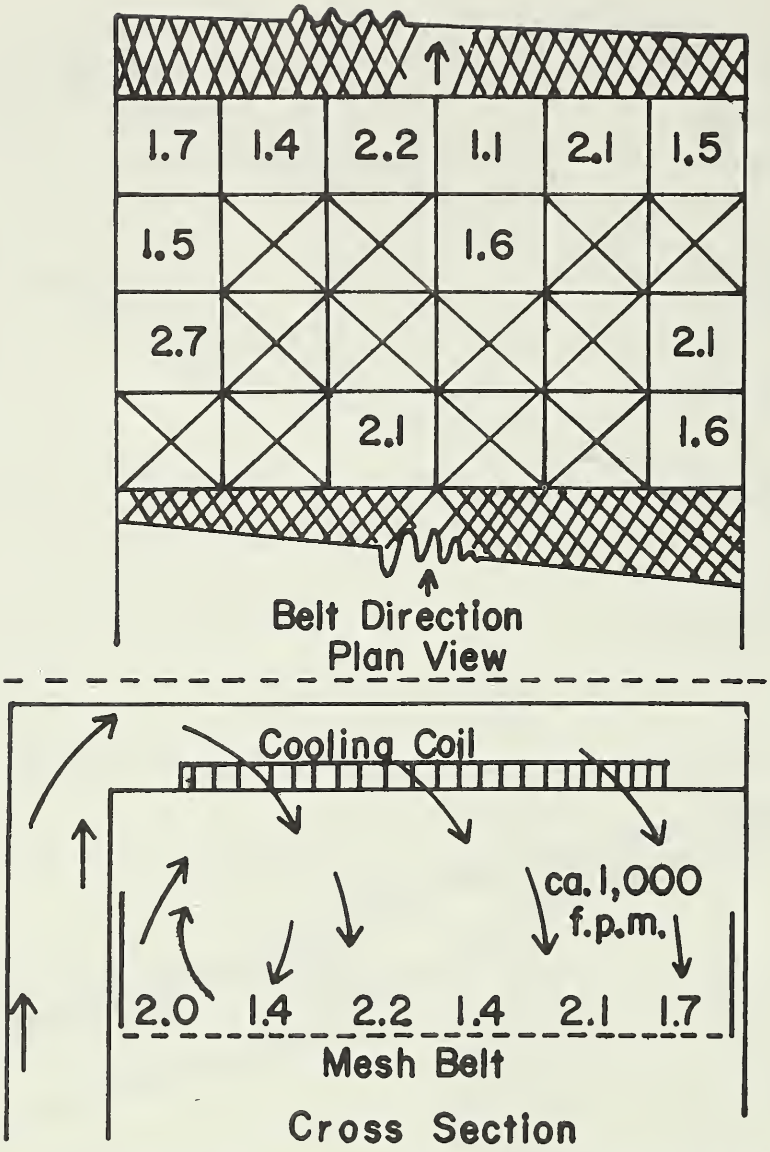

Figure 12.—Mass-average temperature reduction, ° F. per minute, for size 200 Valencia oranges in net Vexar bags cooled 15 minutes. Top, individual bags; bottom, averages by position.

Mass-average temperature was measured in one fruit in each bag. Airflow pattern was analyzed by means of titanium tetrachloride "smoke" in conjunction with a linear flow velometer. A downward flow of air at approximately 1,000 feet per minute was observed on the side farthest from the fan delivery duct. Severe turbulence, having no discernible direction, was observed on the side of the belt nearest the fan delivery ducts.

Reduction in mass-average temperature (fig. 12) was found to vary from 1.1° to 2.7° F. per minute. Rate of cooling was not correlated with airflow pattern nor with rate of airflow at various points across the belt. It is significant that median-sized oranges, initially at 85° F., cooled at a rate of 2.7° F. per minute during a 15-minute cooling period. At this rate, adequate cooling can be achieved during the normal flow of fruit over the packing line. However, this was the maximum cooling rate achieved in these tests.

Another test to evaluate the cooling rate with respect to position on belt as influenced by airflow pattern, was conducted with size 200 Valencia oranges in 4/5-bushel wirebound boxes. Four runs were made (fig. 13). Closed empty cartons were used to fill the empty spaces between test containers to prevent air bypass around the packed boxes. Boxes A and B had air movement blocked on both sides to achieve maximum airflow through the packed boxes. Boxes C and D were arranged so that the air was blocked on one side of the belt, but could flow freely through the other side. These tests were conducted with the precooler adjusted to operate at condition II with a cooling time of 33 minutes. Results are given in table 7.

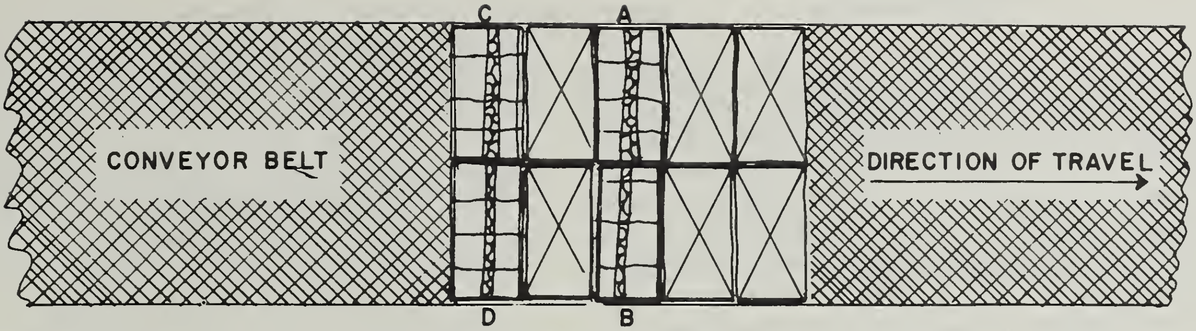

Figure 13.—Distribution of 4/5-bushel wirebound boxes (A, B, C, and D) on conveyor. Closed empty cartons used to block airflow are positioned as shown.

TABLE 7.—Mass-average temperature reduction and cooling rate for size 200 Valencia oranges in open 4/5-bushel wirebound boxes cooled for 33 minutes

[Average of four runs.]

Run[1]	Temperature reduction	Cooling rate
	°F.	°F./min.
A.	52	1.56
B.	33	1.00
C.	42	1.26
D.	36	1.08

[1] Letters A, B, C, and D correspond to those shown in figures 13 and 14.

An interesting and significant result of this test was that cooling occurred at a faster rate on the side of the belt where turbulence was greater than on the side of the belt where a positive downward discharge of air at a linear velocity of 1,000 feet per minute was measured. Time-temperature response of the four tests in this series is illustrated in figure 14. Boxes A and C were on the turbulent side of the conveyor. The time-temperature curves bear out the superior performance of the turbulent side. A mass-average temperature reduction of 40° F. achieved in 13 minutes is clearly indicative of the commercial potential of this type of forced-air precooling system.

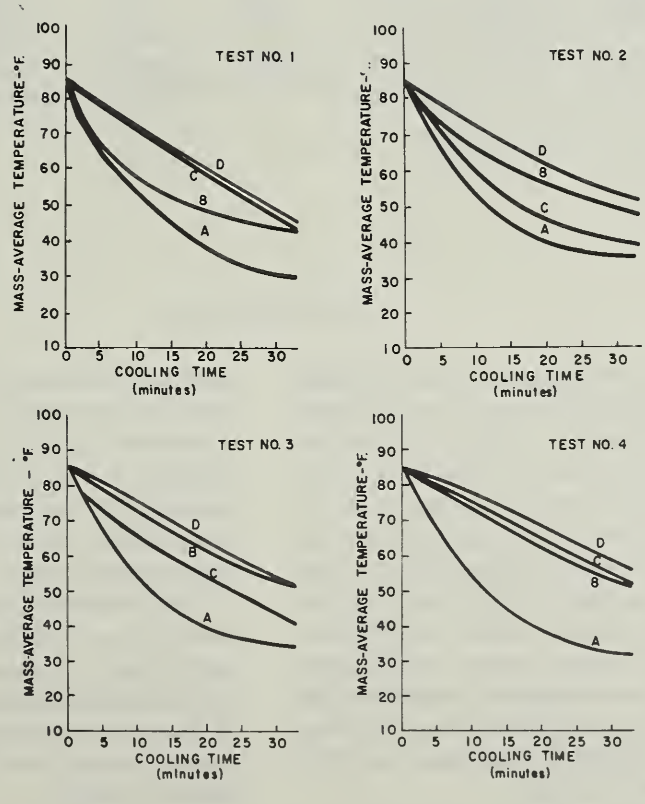

Figure 14.—Mass-average temperature response of size 200 Valencia oranges packed in 4/5-bushel wirebound boxes. Letters A, B, C, and D correspond to position of wirebounds on belt as shown in figure 13.

PERFORMANCE

A measure of performance of the experimental precooler is the quantity of heat removed from the fruit in a given time as compared to the refrigerating capability of the machine. The refrigerating capacity of the precooler when all units are operating at design conditions, is about 15 tons, or 180,000 B.t.u.'s per hour. The precooler has a peak capacity of about 18 tons, but it is doubtful if this is achieved except under the most favorable circumstances. From an average of the seven bulk runs with size 200 Valencia oranges, the average heat removed from the fruit per run was 51,516 B.t.u.'s per hour. The ratio of heat removed from the fruit to design refrigerating capacity is therefore: 51,516 ÷ 180,000 = 0.286. Being a relative measure of performance, based on 100 percent capability, the ratio may be expressed as a measure of efficiency. On this basis, the average efficiency of the forced-air precooler operating at condition II, during the bulk tests, was 28.6 percent. Considering the adverse conditions under which the tests were carried out, this figure is an encouraging indication of performance. Efficiency would tend to be higher for smaller fruit and lower for larger fruit.

The quantity of heat removed from the fruit in each of the seven bulk runs and other corresponding data significant for performance evaluation are outlined in table 8.

TABLE 8.–Electrical energy used as related to heat removed from fruit for respective cooling times on seven bulk runs with Valencia oranges

Cooling time	Total test time	Fruit temperature		Drop	Fruit cooled		Cooling rate	Heat removed	Energy	Efficiency
		In	Out							
Min.	*Min.*	*°F.*	*°F.*	*°F.*	*Lb.*	*Lb./hr.*	*°F./min.*	*B.t.u./hr.*	*Kw.-hr.*	*Percent*
17	71	80.46	66.72	13.74	4,320	3,651	0.8671	48,430	43.6	26.90
20	126	81.90	65.60	16.30	6,019	2,866	.8150	42,047	44.4	23.35
20	111	76.80	58.50	18.30	6,680	3,611	.9150	59,470	52.7	33.03
33	164	79.08	53.74	25.34	4,560	1,661	.7679	37,880	45.7	21.04
33	144	79.10	57.10	22.00	6,380	2,658	.6666	52,635	47.8	29.24
33	113	80.00	59.00	21.00	5,630	2,989	.6364	56,500	44.3	31.38
33	86	81.00	59.20	21.80	4,650	3,244	.6606	63,650	43.4	35.36
Average		79.76	59.98	19.78	5,960	2,954	.7612	51,516	46.0	28.61

CONCLUSIONS

Results of this study substantiated earlier findings (12) that citrus fruit can be satisfactorily precooled with air at temperatures considerably below the freezing point of the fruit. Although citrus fruit can be severely damaged in the grove by exposure to temperatures of 20° to 25° F. for a few hours (4), it can be cooled at these temperatures, or even lower, without injury. This is because sufficient temperature differential can be maintained between the fruit surface and the airstream, provided that the exposure period is short enough and heat diffusion to the surface is adequate to prevent the fruit surface from freezing. (The effect of light freezing of citrus fruits under controlled conditions was also studied and is reported elsewhere (15).)

A mass-average temperature reduction of almost 2° F. per minute for fruit in Vexar bags during a 15-minute cooling period with the precooler under light load shows that under favorable conditions adequate cooling can be accomplished without delay in the movement of fruit through the packinghouse. (As a rule of thumb, a mass-average temperature reduction of 30° F. for oranges and 45° for specialty fruits is adequate for commercial cooling.)

The remaining consideration is cost. Considering the performance of the experimental precooler used in this study, even in light of the adverse operating conditions and malfunctioning equipment, a commercial system can be designed to provide a more efficient cooling rate at correspondingly less cost for operation under packinghouse conditions.

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